AD-A157 112 MULTIAXIAL AND THERMOMECHANICAL FATIGUE CONSIDERATIONS IN DAMAGE TOLERANT DESIGN(U) NATIONAL AERONAUTICS AND SPACE ADMINISTRATION CLEVELAND OH LE.. 1/1

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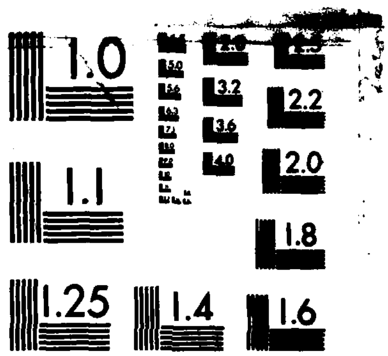

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USAAVSCOM
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Multiaxial and Thermomechanical Fatigue Considerations in Damage Tolerant Design

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Prepared for the
60th Meeting of the Structures and Materials Panel
sponsored by AGARD
San Antonio, Texas, April 21-26, 1985

NASA

1. Report No. NASA TM-87022 USAAVSCOM-TR-85-C-5	2. Government Accession No. AD-A157 112	3. Recipient's Catalog No.
4. Title and Subtitle Multiaxial and Thermomechanical Fatigue Considerations in Damage Tolerant Design		5. Report Date
		6. Performing Organization Code 505-33-7C
7. Author(s) Gail E. Leese and Robert C. Bill		8. Performing Organization Report No. E-2514
		10. Work Unit No.
9. Performing Organization Name and Address NASA Lewis Research Center and Propulsion Laboratory U.S. Army Research and Technology Laboratories (AVSCOM) Cleveland, Ohio 44135		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546 and U.S. Army Aviation Systems Command, St. Louis, Mo. 63120		14. Sponsoring Agency Code

15. Supplementary Notes

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16. Abstract

In considering damage tolerant design concepts for gas turbine hot section components, several challenging concerns arise: Complex multiaxial loading situations are encountered; Thermomechanical fatigue loading involving very wide temperature ranges is imposed on components; Some hot section materials are extremely anisotropic; and coatings and environmental interactions play an important role in crack initiation and crack propagation. In this paper the effects of multiaxiality and thermomechanical fatigue are considered from the standpoint of their impact on damage tolerant design concepts. Recently obtained research results as well as results from the open literature are examined and their implications for damage tolerant design are discussed. Three important needs required to advance analytical capabilities in support of damage tolerant design become readily apparent: (1) a theoretical basis to account for the effect of nonproportional loading (mechanical and mechanical/thermal); (2) the development of practical crack growth parameters that are applicable to thermomechanical fatigue situations; (3) the development of crack growth models that address multiple crack failures.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Fatigue, Damage Tolerance, Multiaxial, High Temperature, Thermomechanical	Unclassified - unlimited STAR Category 26

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified		

*For sale by the National Technical Information Service, Springfield, Virginia 22161

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SUMMARY

In considering damage tolerant design concepts for gas turbine hot section components, several challenging concerns arise: Complex multiaxial loading situations are encountered; Thermomechanical fatigue loading involving very wide temperature ranges is imposed on components; Some hot section materials are extremely anisotropic; and coatings and environmental interactions play an important role in crack initiation and crack propagation. In this paper the effects of multiaxiality and thermomechanical fatigue are considered from the standpoint of their impact on damage tolerant design concepts. Recently obtained research results as well as results from the open literature are examined and their implications for damage tolerant design are discussed. Three important needs required to advance analytical capabilities in support of damage tolerant design become readily apparent: (1) a theoretical basis to account for the effect of nonproportional loading (mechanical and mechanical/thermal); (2) the development of practical crack growth parameters that are applicable to thermomechanical fatigue situations; (3) the development of crack growth models that address multiple crack failures. Additional keywords: High temperature.

INTRODUCTION

The demands for increased service reliability and reduced life cycle costs of aerospace structural components has stimulated the development and application of damage tolerant design concepts to component design. Damage tolerant design procedures are based on the assumed existence of a critically located flaw when the component enters service. The size of the assumed flaw is defined by the sensitivity and reliability of available NDT procedures that can be brought to bear at the critical location. A crack propagation analysis, based on loading representative of the mission profile, is then undertaken to determine the time required for the assumed flaw to grow from a size just below the threshold of detectability to criticality. A "safe fraction" of this time is used to define either an inspection interval or service life, depending on the component retirement philosophy.

Damage tolerant design concepts have been applied to airframe components, at least to the extent that fracture mechanics analyses have been employed (ref. 1). However, engine components, in particular hot section parts, have generally been designed on the basis of crack initiation life using available LCF life prediction procedures. For purposes of providing enhanced engine durability, the military is presently interested in damage tolerant design concepts for engine critical components.

The Air Force has developed a programmed methodology to improve the structural integrity of its engines (ref. 2). This methodology includes consideration of the entire engine life cycle from design inception through scheduled maintenance and finally retirement practices. A key element of this program is the incorporation of damage tolerant concepts in the engine design, combined with mission oriented testing directed toward the identified critical components. However, some special challenges arise when one considers applying damage tolerant design concepts to engine hot section components where complex multiaxial loading, material anisotropy, thermomechanical loading, and time dependent effects are commonly encountered.

The objective of this paper is to examine the effects of multiaxial loading and combined thermal and mechanical (henceforth thermomechanical fatigue - TMF) loading on crack initiation and cyclic crack propagation. These effects will be considered from the standpoint of their impact on damage tolerant design methods. Further, it is the objective of this paper to identify areas of research that will either extend the capabilities of crack growth analysis, or permit the reliable application of uniaxial, isothermal based analyses to more complex situations.

Multiaxial Fatigue

In the laboratory, multiaxial mechanical testing implies an excursion from traditional tensile or uniaxial fatigue tests, where two of the three principal stresses are zero. Biaxial fatigue testing is typically performed via combined tension and torsion cyclic loading on smooth round specimens. Such loading can be proportional (in-phase) such that the maximum and minimum loads of each cycle occur simultaneously or nonproportional (out-of-phase), such that a controlled phase difference exists between the two loads, resulting in changing directions of principal stress throughout the cycle. In addition to multiaxial stress states produced mechanically, thermal cycles may be applied producing in-phase or out-of-phase strains with respect to the mechanical profile.

The pertinence of such research in aircraft gas turbine engines is becoming more obvious as structural analysis techniques improve the description of the multiaxial stress states of hot path components. In recent NASA sponsored research (ref. 3) the biaxial stress state in a disk bore that would evolve from a realistic, simulated mission was presented as a complex spectrum of nonproportional, variable amplitude tangential and axial stresses (fig. 2). In that same report it's suggested that vanes and combustor liners are likely to experience equally complex loading profiles. Frequently the nonproportional characteristics of such loading profiles results from the superposition of mechanical and thermal loads. Hence how to deal with multiaxial loading environments, as well as how to incorporate these solutions into design concepts such as a damage tolerance, are relevant topics to existing engineering needs in the aeronautics and aerospace industries.

Applicability of Uniaxial Results

Many investigators have targeted their research towards the development and demonstration of ways of using existing uniaxial materials properties and response for the resolution of multiaxial problems. The most straightforward biaxial laboratory test germane to this effort is an isothermal constant amplitude torsion test. In this case the extrapolation of uniaxial fatigue strain-life properties to the biaxial stress state is frequently made by altering the power law strain-life relationships using conventional techniques. The axial representation of total strain-life law is (refs. 4 to 6):

$$\Delta\varepsilon_t = 2\varepsilon_f'(2N_f)^{-C} + \frac{2\sigma_f'}{E}(2N_f)^{-b}$$

Where σ_f' is the fatigue strength coefficient, E the Young's Modulus, N_f the cyclic life, ε_f' is the fatigue ductility coefficient, and $\Delta\varepsilon_t$ the total strain range.

The fatigue ductility and strength exponents, c and b, have been shown to be stress state independent at room temperature for several materials in these simple loading cases (refs. 7 and 8) and are therefore usually assumed to be constant. Some form of effective or equivalent criteria (such as von Mises or Tresca) is then used to modify the ductility and strength coefficients for the stress state of interest (fig. 3). This approach is often adequate for the projection of fatigue properties in a simple stress state from another simple stress state.

However, in more complicated profiles that actually describe realistic component histories, including mean stresses, variable amplitude and nonproportional thermal and mechanical loading, there is no obvious way to extrapolate axial fatigue properties to the multiaxial environment. Indeed, the very accuracy of such an approach would be questionable for several reasons. Recent investigations have shown that nonproportionality as well as sequence effects of variable amplitude biaxial loading affect the cyclic ductility, as well as the cyclic strain hardening exponent (refs. 9 and 10). Also, the actual modes of failure may vary with the bulk stress state applied, greatly reducing the physical basis on which one would justify such methodology.

Multiaxial Crack Propagation

Biaxial loading (primarily tension/torsion) of laboratory specimens in strain control has shown that the resulting bulk damage states can be classified into two categories (refs. 7 and 11):

(1) Multiple crack systems, showing complex behavior of mixed mode growth and crack interactions, typically occurring in high strain, low cycle conditions.

(2) Single dominant crack initiation and growth, characteristic of low strain, high cycle conditions.

These same trends have been observed in axial loading (ref. 12), but due to recent advances in multiaxial testing capabilities, it has become apparent that they're greatly accentuated in multiaxial conditions, and cannot be overlooked as being merely of academic interest.

The multiple crack system response observed in high strain biaxial conditions is most interesting due to the complexity of the phenomenon, and due to the engineering implications in situations where finite life prediction is necessary. Testing laboratory specimens in torsion and combined tension/torsion promotes the initiation of cracks on planes of maximum shear stress at multiple sites. Early cracks form throughout the test section, grow to a size small in comparison to the specimen geometry, after which the growth is arrested while additional small cracks continue to start the same process. These cracks will grow along the specimen surface in planar shear, some linking with others until the resultant fissures are quite large relative to the specimen dimensions. Upon linking and growing in length on the surface, these cracks will eventually propagate through the thickness of the specimen in antiplane shear, a mode of crack propagation quite different in terms of crack growth rate and critical crack lengths from that of surface crack propagation. It is this through thickness propagation that causes rapid degradation of the load carrying capability of a specimen.

Figure 4 shows this multiple cracking phenomenon in replicas of Waspaloy tested in torsion at room temperature. Similar modes of cracking have been reported with Hastelloy X.

These observations of multiple crack systems aren't peculiar to disk superalloys, and therefore have implications beyond the immediate application to disk materials. In figure 5, similar multiple cracking patterns, observed early in the life of Inconel 718 are shown in replicas taken progressively throughout a strain controlled test at room temperature. To contrast further, medium carbon steels also exhibit these cracking modes in biaxial loading, as seen in the progression of cracking throughout the life of a 1045 steel in figure 6.

Of course, it is the interest in high temperature response that adds to the complexity of multiaxial fatigue in superalloys. We have found that, from a bulk failure viewpoint, the temperature dependent aspects are important in determining the critical planes housing the early multiple cracks. Figure 7 shows the through thickness cracking that caused loss of load carrying ability in torsionally loaded Waspaloy at room temperature and at 650 °C (1200 °F). At room temperature the shear mode dominated initiation and failure on longitudinal shear planes, whereas at elevated temperature, the final failure occurred on the 45° planes across which the maximum principal stress occurs in torsion.

One might wonder whether the response of smooth, unnotched laboratory specimens is representative of the critical crack in the notched component that is addressed by damage tolerant design codes. There is very little information available generated from the controlled multiaxial testing of notched specimens, since this type of work is more on the order of component testing than research. However, experimental programs including combined bending and torsion on notched shafts have reported the same multiple initiation site behavior as seen in the smooth specimen tests. Until further experimentation shows otherwise, it is prudent to assume that notches in hot section components do not reduce the failure response to a single crack phenomena.

Single dominant crack failures, whether in axial or multiaxial stress states, obviously lend themselves to damage tolerant concepts directly. In the multiaxial case, the single crack may be growing in a mixed mode manner such that this must be considered in the methods of analysis. There is currently ongoing research under sponsorship of many different organizations investigating mixed mode crack growth.

TMF EFFECTS

Where are TMF Effects Significant?

Two idealized but representative TMF cycles are shown in figure 8, illustrating several significant features and parameters that together define the type and severity of the TMF cycle. An important feature is of course the temperature range represented by T_{max} and T_{min}. The phase relationship between the mechanical loading cycle and the temperature cycle can have a major effect on TMF life. Figure 8 shows both an "in-phase" cycle wherein the material is under tensile load at the maximum temperature, and an "out-of-phase" cycle in which the material is under compression at the maximum temperature. The mechanical loading parameters that define the TMF cycle include the maximum, minimum, and mean stresses as well as the total strain range and the inelastic strain range.

In general, significant TMF effects on crack initiation and propagation lives are observed when the cyclic temperature range is large enough that significant variation in material mechanical behavior occurs. These conditions are certainly encountered during the operating cycle experienced by combustor liners, turbine airfoils, and to a lesser extent, turbine disk rims. Examples of TMF loading for critical locations of each of these components are shown in figure 9 (refs. 13 to 15). Both the turbine blade tip and the combustor liner are clear cases of out-of-phase cycling. In fact out-of-phase TMF cycles are more generally encountered in hot section components than are in-phase cycles. The disk rim example could also be considered an out-of-phase case with a high tensile mean stress since the maximum tensile stress occurs near the minimum temperature.

As is the case for isothermal fatigue, TMF life consists of a crack initiation stage followed by a crack propagation stage. Although the crack propagation stage is most pertinent to damage tolerant design, a brief consideration of initiation will help to establish some general trends and the overall significance of TMF cycle parameters on life.

Effects of TMF on Initiation Life

Analysis of component TMF life is presently based on isothermal life prediction models, some examples of which are listed in table I. All of these models incorporate as input either the total or inelastic strain range, sometimes combined with various methods of accounting for interaction between time-dependent inelastic strain (creep) and cyclic plasticity. In some cases mean stress and maximum tensile stress effects are included in the life prediction models. Reference 16 summarizes the applicability of some of these models to TMF life prediction of a turbine blade alloy.

The experimental results in figures 10 and 11 compare the TMF lives of two different turbine airfoil materials with results for isothermal testing. Unfortunately, comparable results are not available for a disk alloy. The tests were conducted in such a manner that the indicated lives are predominantly crack initiation lives.

Consider first the results for MAR-M 200 shown in figure 10. The in-phase TMF lives are an order of magnitude lower than the isothermal lives, regardless of whether the isothermal data corresponding to the maximum TMF cyclic temperature or minimum temperature is used for comparison. The out-of-phase results however are comparable to the low temperature isothermal results.

The TMF crack initiation results for B-1900 show the same general trends as those for MAR-M 200, as may be seen in figure 11. The in-phase lives are as much as an order of magnitude lower than corresponding isothermal lives. However, the out-of-phase results correspond more closely to the range of isothermal lives.

Although published TMF data is very limited, the results presented in figures 10 and 11 are believed to be representative of the behavior one would see in a broad range of nickel based superalloys. A major phenomenon not generally predicted by the isothermal initiation life models is the relative ranking of the in-phase versus out-of-phase cycles. Most isothermal models are so structured with respect to the role of tensile stress or mean stress that out-of-phase lives would be predicted to be lower than in-phase. Apparently TMF cycling is introducing effects not captured in the isothermal models. However, crack propagation behavior under TMF conditions turns out to be more reliably predictable on the basis of isothermal behavior.

Effects of TMF on Crack Propagation

Some results from Pelloux's research on cyclic crack propagation under TMF conditions are summarized in figure 12 (ref. 17). The experiments were conducted on Inconel X-750, both in-phase and out-of-phase over a temperature range of 300 to 650 °C, representing disk rim conditions. A striking observation is that the highest crack propagation rates occurred under out-of-phase cycling conditions, with crack growth an order of magnitude faster than under comparable isothermal conditions. Note that this phasing effect is the inverse of that seen in initiation dominated experiments. Crack growth for in-phase cycling was between the rates of isothermal and out-of-phase test. Pelloux attributes the high crack growth rates under out-of-phase conditions to nonclosure at zero load, and shows that good correlation between TMF crack growth rates and isothermal results is realized if nonclosure is accurately accounted for by substituting ΔK_{eff} for ΔK as illustrated in figure 13. The practical difficulty here is accurately defining ΔK_{eff}, i.e., analytically quantifying crack nonclosure, in the design of a turbine disk. Failure to do so would introduce potentially serious nonconservative errors in the predicted component crack growth life. It would appear that application of damage tolerant design to components subjected to significant TMF loading using linear elastic fracture mechanics (LEFM) principles will require considerable component and mission specific specimen testing as support.

Rau, Gemma and Leverant (ref. 18) conducted TMF crack propagation experiments similar to those of Pelloux, but on turbine airfoil materials and over a broader temperature range (320 to 900 °C typically). The results were correlated with cyclic strain intensity as the LEFM parameter. The same general trends were observed as for Inconel X-750 cited above, with crack propagation rates for out-of-phase cycling being significantly higher than for in-phase or isothermal cycling. These trends were attributed to oxidation assisted crack sharpening effects that may occur during the compressive portion of out-of-phase cycling. Again, accounting for these effects in the course of damage tolerant design analysis is difficult and errors incurred if isothermal crack propagation results alone are employed in conjunction with LEFM are likely to be nonconservative.

Jordan and Meyer (ref. 19) looked at the TMF crack propagation of Hastelloy-X from the standpoint of predicting TMF behavior on the basis of isothermal results. They developed a crack growth model based on ΔK_E with built-in corrections for temperature dependent crack growth rates determined in isothermal cycling. This model actually predicted TMF growth rates to within a factor of two to three of their experimental data, but was sometimes nonconservative and sometimes conservative, depending on loading conditions.

TMF crack propagation experiment conducted on a series of steel alloys important in the power generating industry were reported by Okazaki and Koizumi (ref. 20). Though no direct comparisons with isothermal cycling fatigue data are shown, the authors did demonstrate very accurate predictions of crack propagation rate under TMF cycling using a J-Integral model. The accuracy of their prediction stems no doubt from their use of material hardening parameters determined from TMF cyclic stress-strain data. These cyclic constitutive parameters could, however, be determined in a test of limited duration not requiring the test time associated with crack growth measurement and life determination.

CONCLUSIONS

From the foregoing discussion of published results it is readily apparent that both multiaxial fatigue and thermomechanical fatigue have a significant impact on crack initiation and crack propagation. Several specific research needs and results are evident that will provide necessary improvements to crack propagation analysis, a vital part of damage tolerant design:

1. Theoretical basis to account for effects of nonproportional loading (mechanical and mechanical/thermal).

2. Crack growth models that address multiple crack failures.

3. Mixed mode failure models.

4. Development of practical crack growth parameters that are applicable to TMF load situations.

5. General trends including the effect of TMF cycle phasing appear to be applicable to a broad range of materials both from crack initiation and crack propagation standpoints.

6. Trends for TMF crack initiation may generally be very different from those for TMF crack propagation.

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TABLE I

HIGH TEMPERATURE LOW CYCLE FATIGUE MODELS AVAILABLE

- **MANSON - COFFIN RULE**

$$N_{PRED} = (C/\Delta\epsilon_{in})^{1/c}$$

- **METHOD OF UNIVERSAL SLOPES**

$$\Delta\epsilon_{TOT} = D^{0.6} N_f^{-0.6} + 3.5\, \sigma_u/E\, N_f^{-0.12}$$

- **STRAIN RANGE PARTITIONING**

$$1/N_f = F_{ij}/N_{ij} \;;\; ij \Rightarrow (pp,\ pc,\ cp,\ cc)$$

$$F_{ij} = \Delta\epsilon_{ij}/\Delta\epsilon_{IN}$$

$$N_{ij} = (C_{ij}/\Delta\epsilon_{IN})^{1/c}$$

- **OSTERGREN MODEL**

$$\sigma_t \Delta\epsilon_p [N_f \nu^{(K-1)}]^{\beta} = C$$

- **FREQUENCY SEPARATION MODEL**

$$N_f = D\Delta\epsilon_p \nu_T^{b} (\nu_c/\nu_T)^{c}$$

- **DAMAGE RATE MODEL**
- **TIME AND CYCLE FRACTION MODEL**

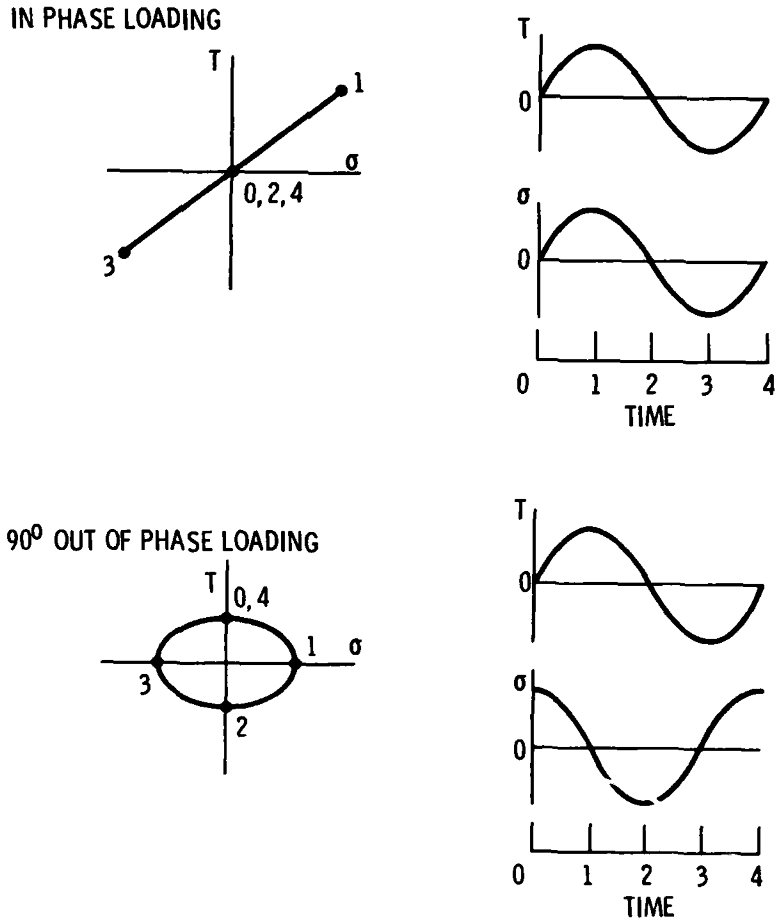


Figure 1. - In-phase and out-of-phase tension-torsion loading.

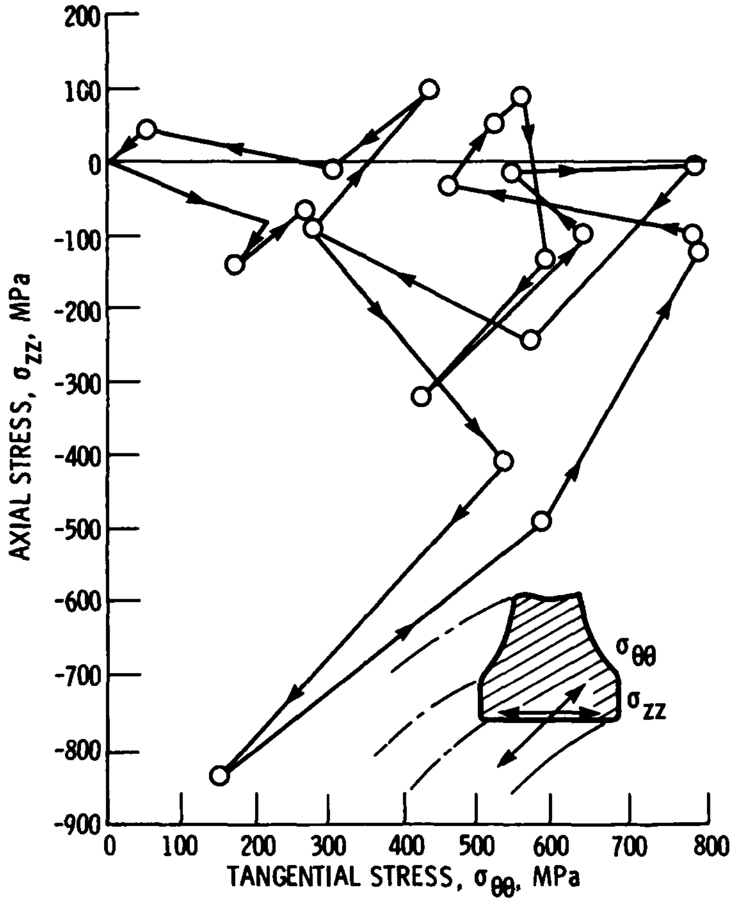


Figure 2. - Example of the complex states of stress that can evolve during a simulated mission in a disk bore.

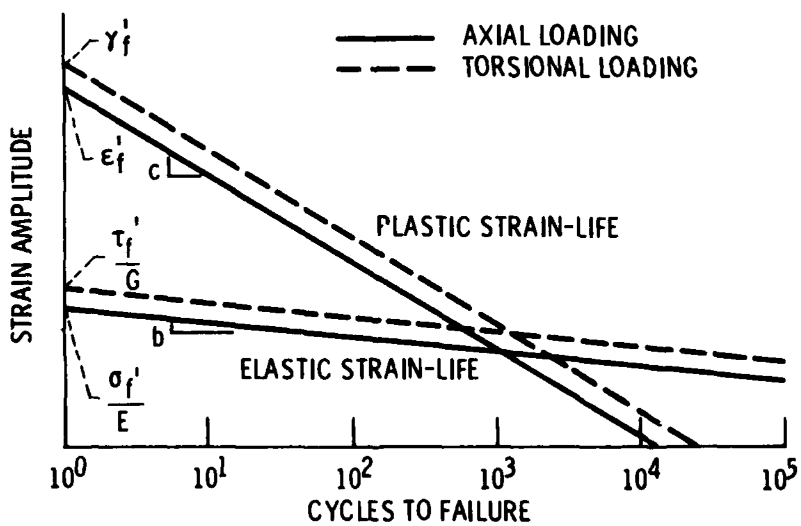


Figure 3. - First approximation of strain-life relationships in different stress states, assuming stress state independent slopes and modified strength and ductility coefficient.

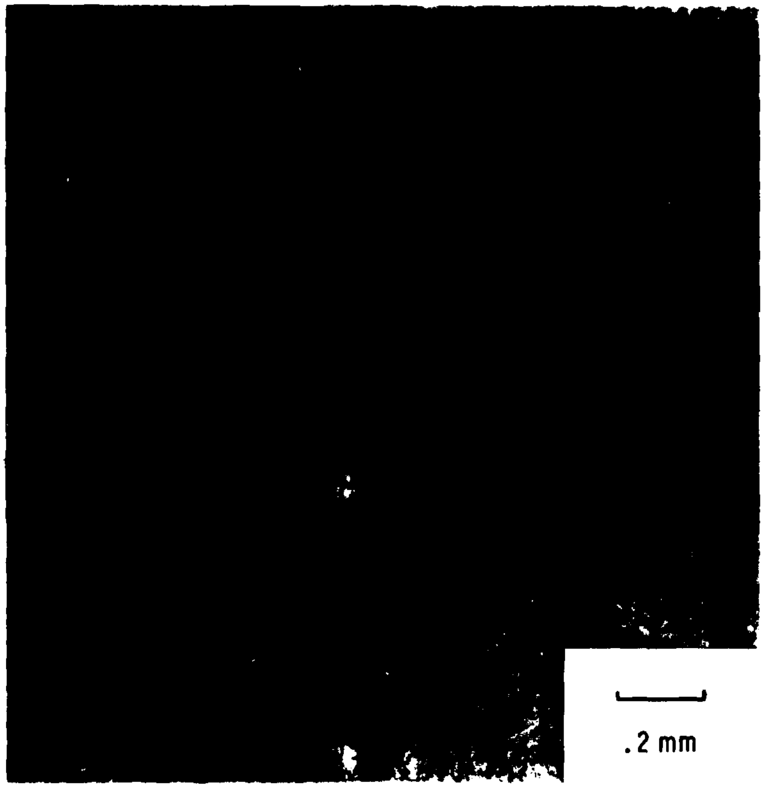


Figure 4. - Replicas showing multiple cracking in Waspaloy sublected to torsional loading ($_a$ = 0.0196) at room temperature (N_f = 3965). (Courtesy of Prof. S.Y. zamrik, Pennsylvania State University, NASA Grant No. NAG3-264.)

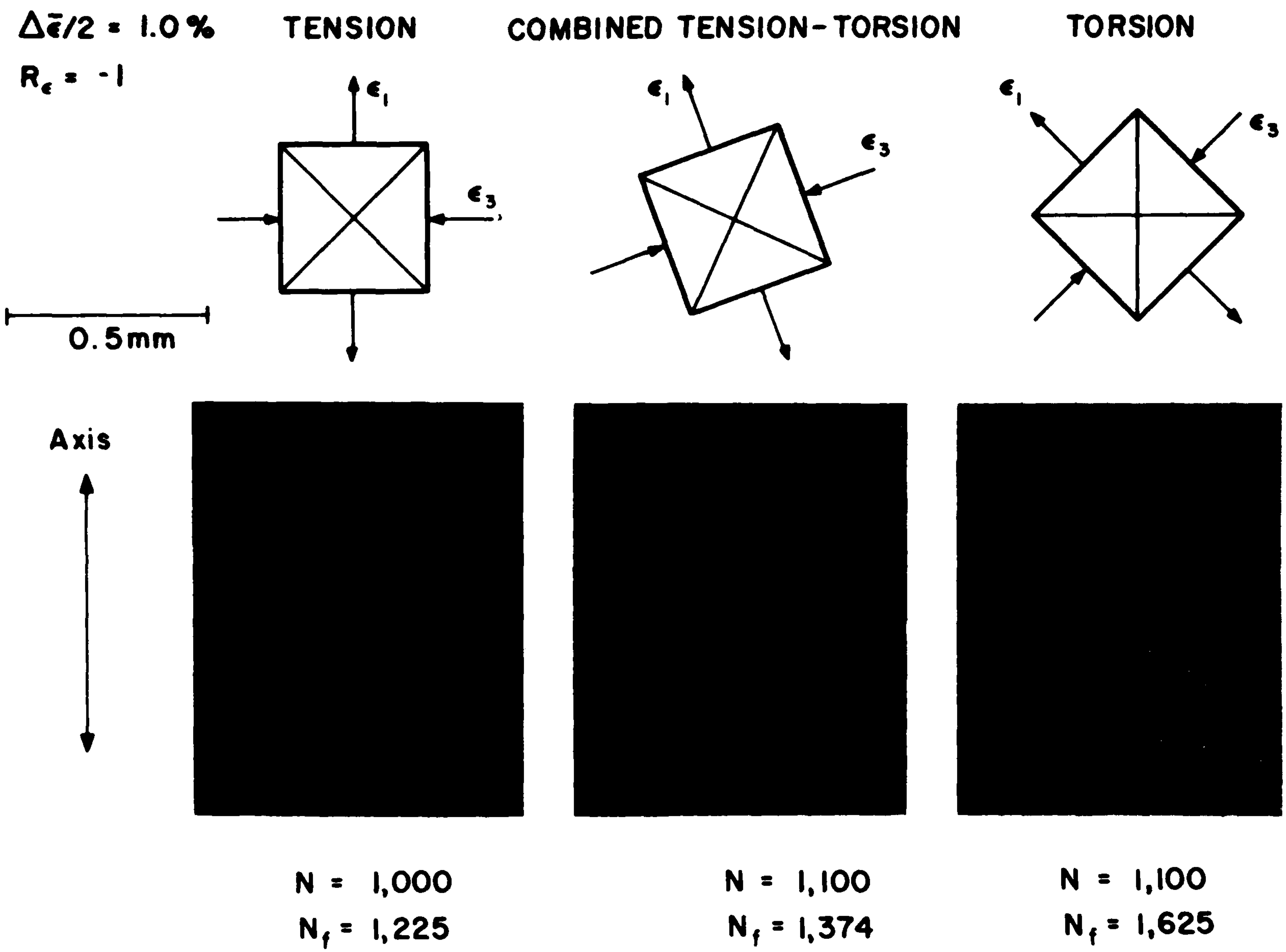
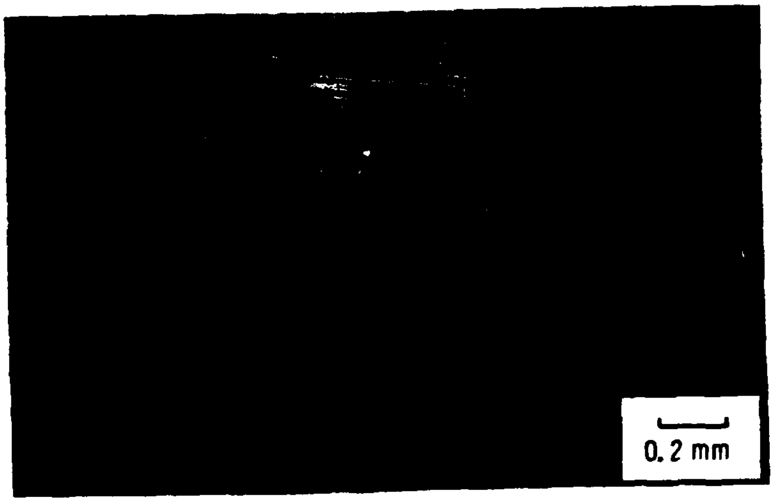
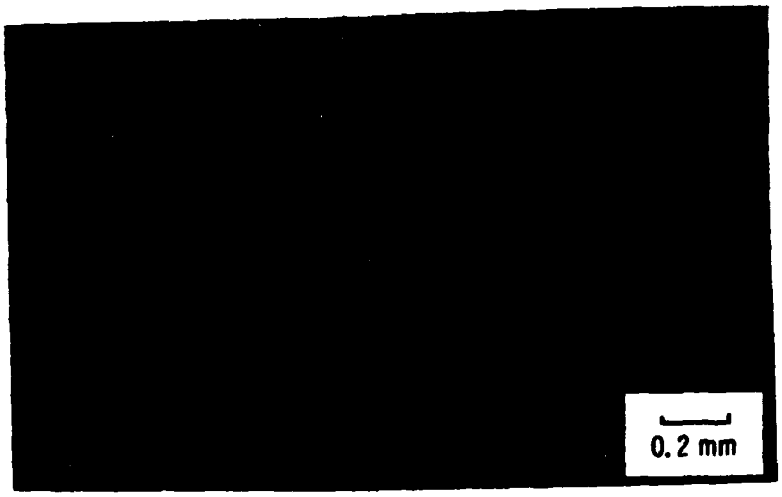


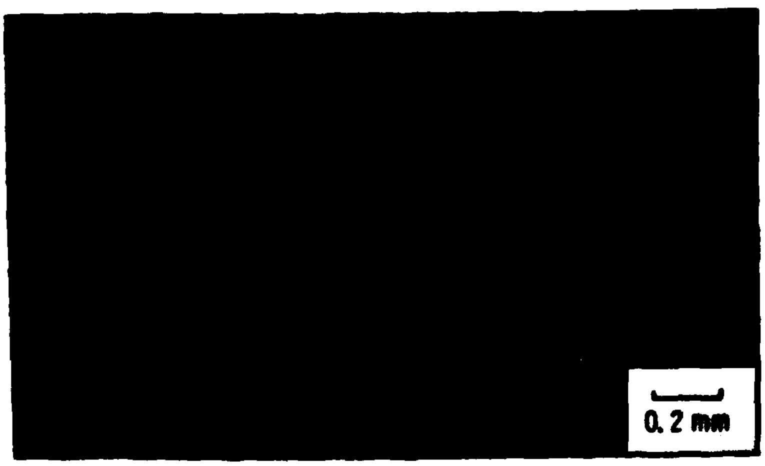
Figure 5. - Progressive multiple cracking in Inconel-718 under tension-torsion loading. (Courtesy of Prof. D. F. Socie, University of Illinois, NASA Grant No. NAG3-465.)



(a) After 518 cycles.

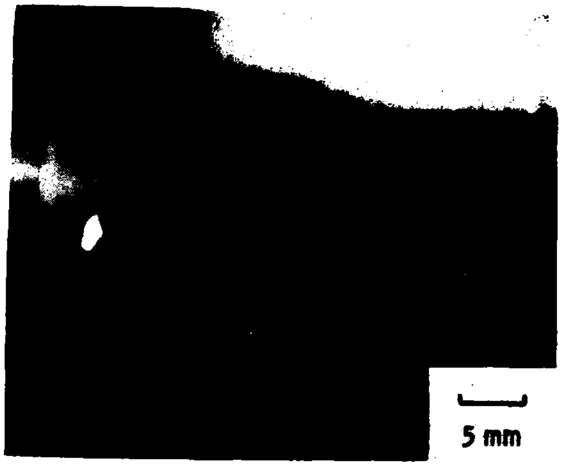


(b) After 9266 cycles.

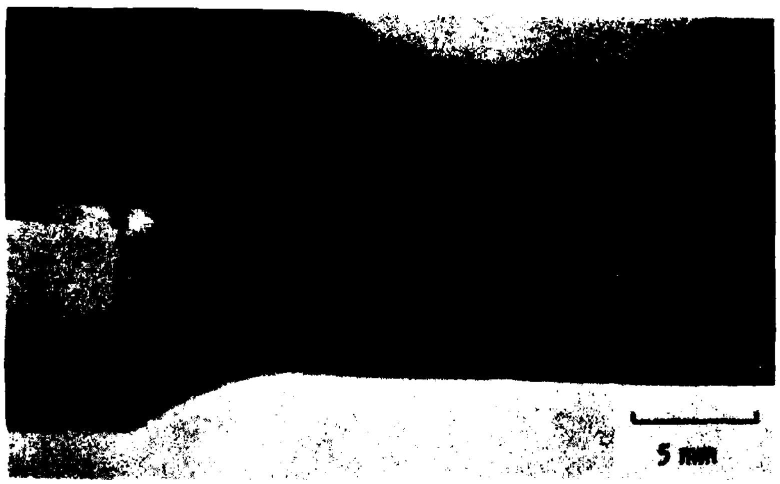


(c) After 10390 cylces.

Figure 6. - Progressive multiple cracking in medium carbon steel. $\gamma_a = \pm .8\%$; $2N_f = 11010$.

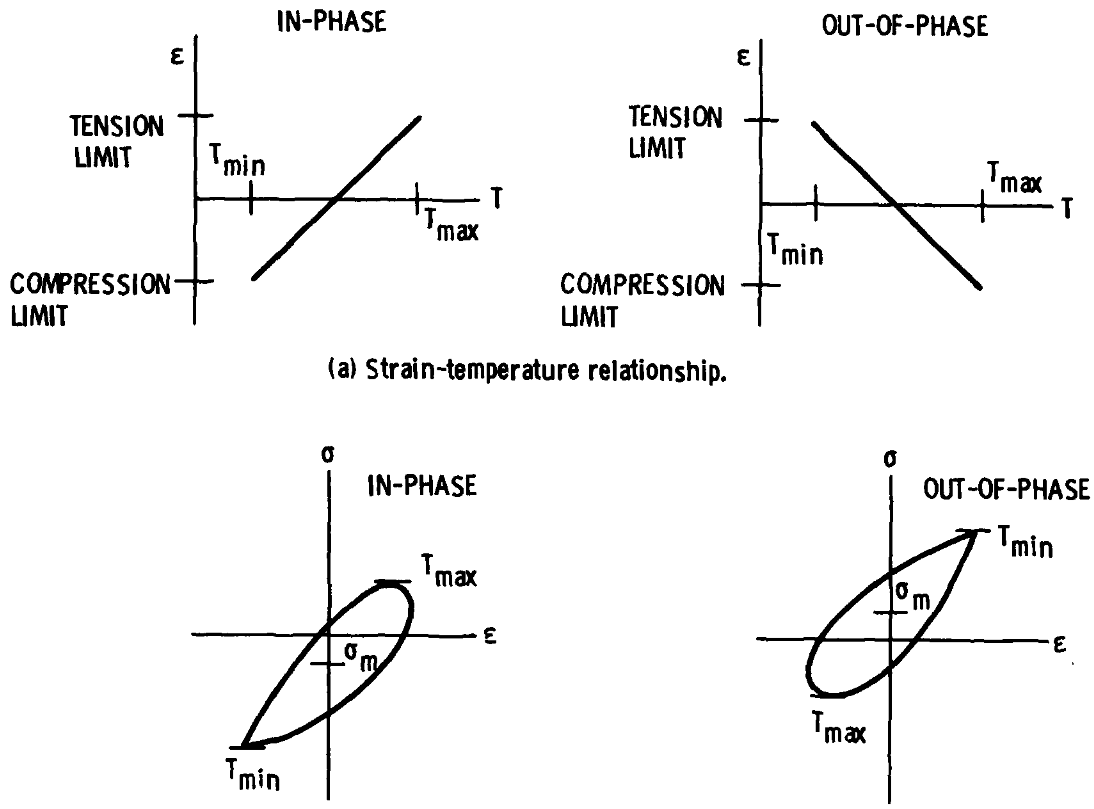


(a) Fine grain showing cracking on maximum shear planes, room temperature.



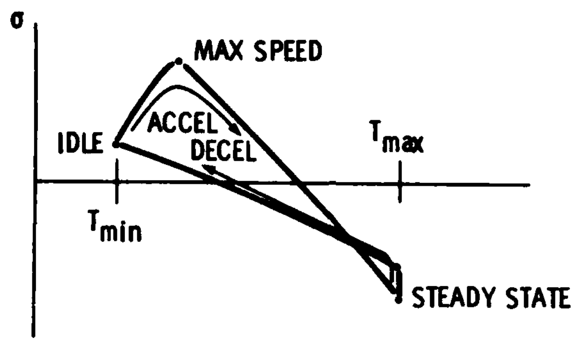
(b) Coarse grain showing cracking at 45^0 to specimen axis on planes of maximum tension, 650 °C.

Figure 7. - Macrophotos showing primary cracks in fine grain and coase grain Waspaloy multiaxial specimens subjected to cyclic torsion. (Courtesy of Prof. S. Y. Zamrik, Pennsylvania State Universitv. NASA Grant No. NAG3-264.)

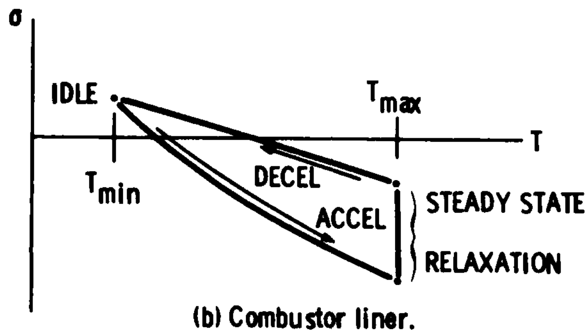


(b) Stress-strain relationship.

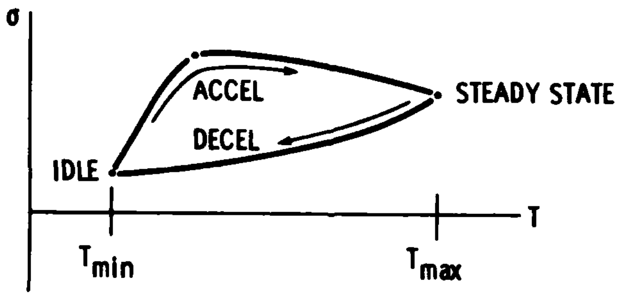
Figure 8. - Typical TMF test cycles showing mechanical strain versus temperature, and stress-strain relationships for in-phase and out-of-phase cycles.



(a) Turbine airfoil.



(b) Combustor liner.



(c) Disk rim.

Figure 9. - TMF loading cycle schematics representative of turbine airfoils, combustor liners and disk rims.

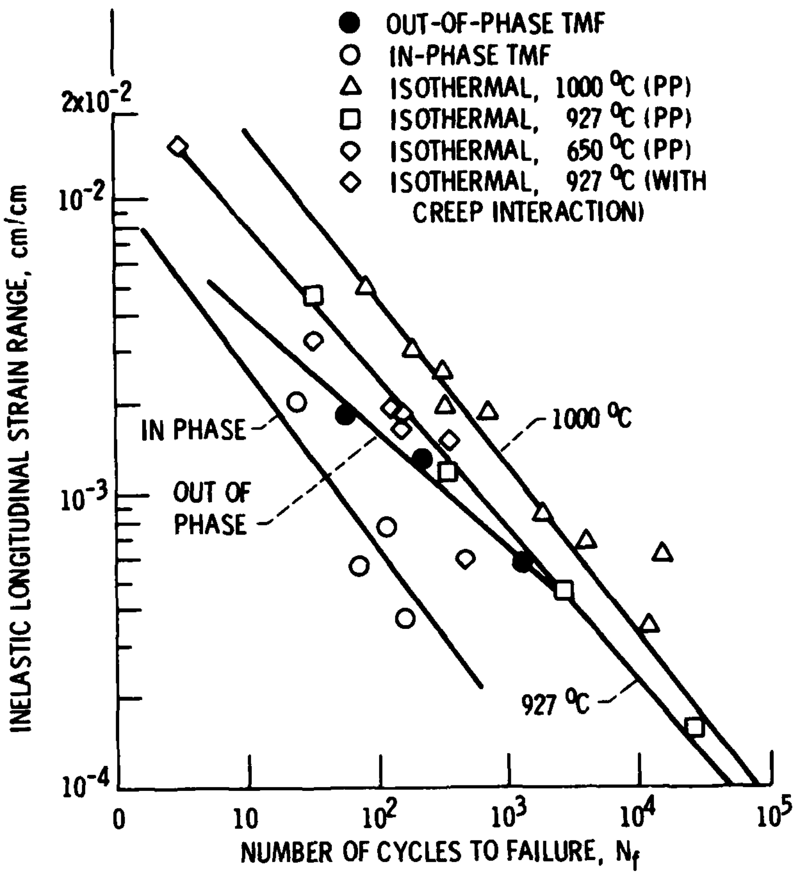


Figure 10. - Inelastic strain range as function of number of cycles to failure for polycrystalline MAR-M 200 under thermomechanical fatigue and isothermal cycling conditions.

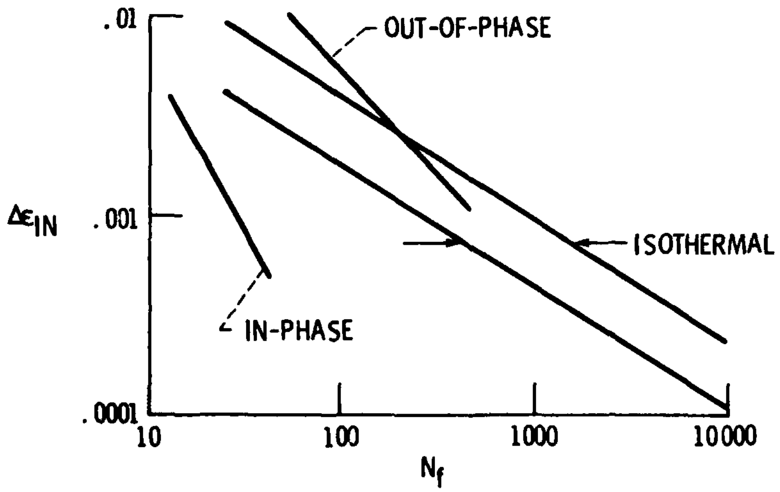


Figure 11. - In-phase and out-of-phase TMF lives compared to isothermal lives for B-1900 cycled between 520 °C and 870 °C.

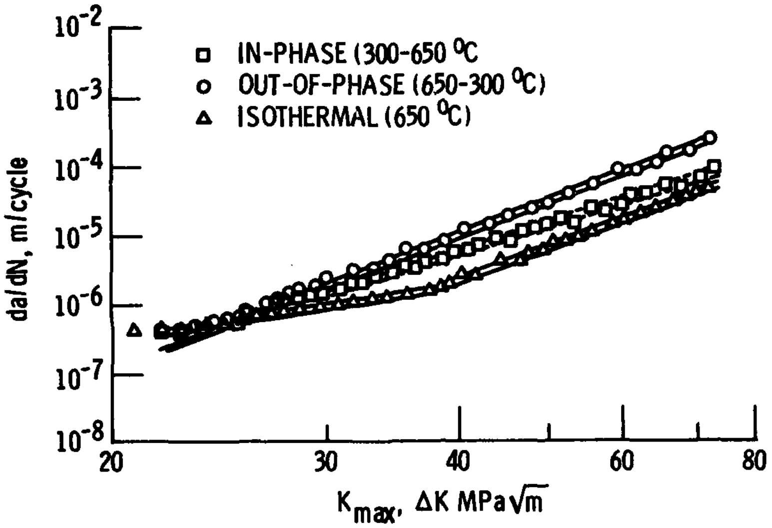


Figure 12. - Thermomechanical fatigue crack growth in Inconel X-750 as a function of ΔK, based on K_{max}, K_{min}.

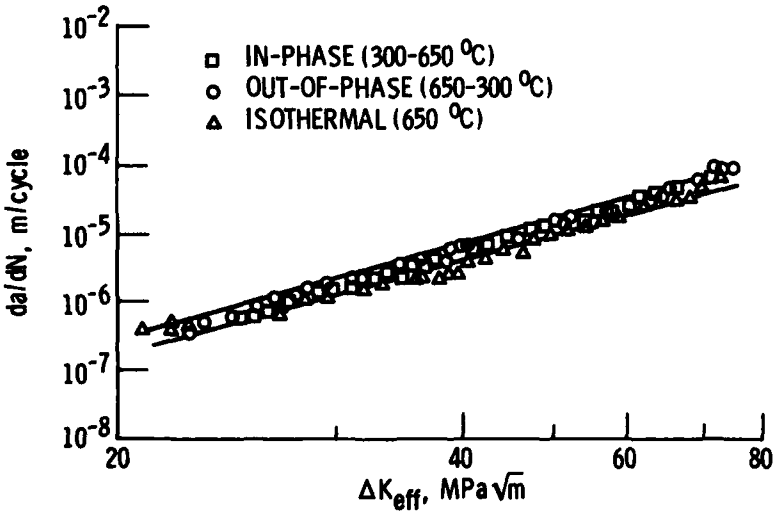


Figure 13. - Thermomechanical fatigue crack growth in Inconel X-750 as a function of ΔK_{eff}, accounting for crack closure effects.

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